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Dynamics of electric field domain walls in semiconductor superlattices

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Abstract

A self-consistent microscopic model of sequential tunneling in superlattices is employed to investigate self-sustained current oscillations. Current spikes – high-frequency modulation due to well-to-well hopping of charge monopole domain walls – are naturally reproduced. Moreover, as the contact doping shrinks, the recycling and motion of charge dipoles resulting in a lower-frequency oscillatory mode is predicted. For low contact doping, this mode dominates and monopole oscillations disappear. At intermediate doping, hysteresis between both the oscillatory modes may be possible.

Keywords: Superlattices; High field effects; Tunneling domains

Vertical transport in weakly coupled semiconductor doped superlattices (SLs) has been shown to display nonlinear phenomena such as electric field domain formation, multistability, self-sustained current oscillations, and driven and undriven chaos [1]. When the carrier density is set below a critical value, self-sustained oscillations of the current may appear in voltage biased SLs. They are due to the periodic dynamics of the domain wall (DW), which consists in a charge monopole accumulation layer or a *monopole*, separating two nearly constant electric field domains [2]. Monopole motion and recycling have been experimentally shown by counting the spikes – high-frequency modulation – superimposed on one period of the current self-oscillations: current spikes correspond to well-to-well hopping of a DW through the SL [3]. Our purpose is to extend the model proposed in Ref. [4] for the stationary case to include the time dependence of the current. We analyze the tunneling current through the SL by means of the transfer Hamiltonian. The dynamics is considered in the model through the Ampère's law for the total current density $J = J(t)$:

$$J = J_{i-1,i} + \frac{\varepsilon}{d}\frac{dV_i}{dt}. \tag{1}$$

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Here $J_{i-1,i}$ is the tunneling current density through the ith barrier of thickness d:

$$J_{i,i+1} = \frac{2e\hbar k_B T}{\pi^2 m^*} \times \sum_{j=1}^{n_{max}} \int \frac{\gamma}{[(\varepsilon - \varepsilon_{ri}^1)^2 + \gamma^2]} \frac{\gamma}{[(\varepsilon - \varepsilon_{ri+1}^j)^2 + \gamma^2]} \times T_{i+1}(\varepsilon) \ln \left[\frac{1 + e^{(\varepsilon_{\omega_i} - \varepsilon)/k_B T}}{1 + e^{(\varepsilon_{\omega_{i+1}} - \varepsilon)/k_B T}} \right] d\varepsilon, \quad (2)$$

where ε_{ri}^j is the jth resonant state of the ith well (n_{max} is the number of subbands participating in the transport) and $T_i(\varepsilon)$ is the transmission through the ith barrier. Note that only the lowest resonant level is assumed to be populated. Scattering is treated phenomenologically by considering the spectral functions of the wells as Lorentzians (γ is the half width). The last term in Eq. (1) is the displacement current at the ith barrier where the potential drop is V_i and ε is the static permittivity. We include the Coulomb interaction in a mean field approximation by means of discrete Poisson equations relating the potential drops in wells, barriers and contacts. The boundary conditions at the contacts describe the lengths of the depletion and accumulation layers as well as the charge density at the leads. The final set of equations solved self-consistently [4]. We have studied a 50-well 13.3 nm GaAs/2.7 nm AlAs SL at $T = 0$ K [3]. Doping in the wells and in the contacts are $N_w = 2 \times 10^{10}$ cm^{-2} and $N_c = 2 \times 10^{16}$ cm^{-3}.

For the sake of brevity, the monopole-mediated self-oscillations are not depicted here, and can be found elsewhere [5]. Instead, we shall focus on dipole self-oscillations akin to those in the Gun effect [2]. Since an advantage of our present model over other discrete ones [1,2] is the microscopic modelling of boundary conditions, we can study what happens when contact doping is changed. The result is that dipole-mediated self-oscillations appear as the emitter doping is lowered below a certain value. There is a range of voltages for which dipole and monopole oscillations coexist as stable solutions. When the emitter doping is further lowered, only the dipole self-oscillations remain. Fig. 1 presents data in the crossover range (below $N_c = 4.1 \times 10^{16}$ cm^{-3} and above $N_c = 1.7 \times 10^{16}$ cm^{-3} for the second plateau) for the sample values given above, applying a DC bias voltage of 5.5 V. These self-oscillations have

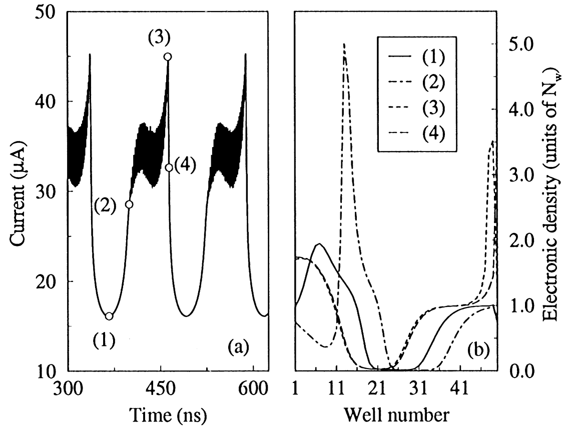

Fig. 1. (a) Dipole-mediated self-sustained oscillations of the total current through the SL. Bias is 5.5 V and the contact doping is $N_c = 2 \times 10^{16}$ cm^{-3}. (b) Evolution of the well density at the times marked in (a). When a sharp accumulation layer is formed at (2), it starts to get through the SL and spikes arise. The DW leaves a depletion region on its wake (see (3)). Eventually, it dies in the collector at (4) while it is recycled at the emitter (more clearly seen in (1)).

not been observed so far in experiments due to the high contact doping adopted in all the present experimental settings. What is remarkable in Fig. 1(a) (as compared to previous studies) are the spikes superimposed on one side of the oscillations. Such spikes have been observed experimentally and attributed to well-to-well hopping of the DW [3]. Between each two peaks of $J(t)$, we observe 36 additional spikes. Thus dipole recycling and motion occur on almost the whole SL (roughly between the 10th and the 50th well) and accompany the current oscillation. In the experiments performed up to now, self-oscillations present a markedly smaller number of spikes, indicating that they are due to monopole recycling [3,2].

Fig. 2(a) depicts a zoom of the spikes in Fig. 1(a). They have a frequency of about 500 MHz and an amplitude of 5.5 μA. Fig. 2(b) shows the charge density profile at four different times of a current spike marked in Fig. 2(a). Notice that the electron density in Fig. 2(b) is larger than the well doping at only three wells (24, 25 and 26) during the times recorded in Fig. 2(a). The contributions of tunneling and displacement currents to $J(t)$ in Eq. (1) are depicted in Figs. 2(c) and (d).

The spikes reflect the two-stage hopping motion – fast time scale – of the DW. During the stage where

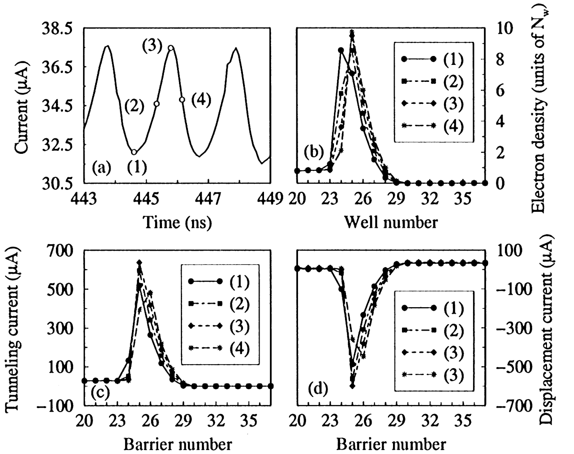

Fig. 2. (a) Zoom of Fig. 1(a) showing the spikes of the current. (b) Electron density profiles (in units of the doping at the wells), (c) tunneling current, and (d) displacement current at the times marked in (a). Notice that after the 29th well the SL is significantly depleted of electrons.

the current rises, charge is mainly transferred through a single barrier, for at time (1) (minimum of the current) the charge accumulates mainly at the ith well (the 24th well in Fig. 2(b)) and then electrons tunnel from this well to the next one, the $(i+1)$th, where most of the charge is located at time (3) (maximum of the current). Between times (1) and (3), the tunneling current is maximal where the displacement current is minimal and the total current increases. After that, some charge flows to the next well [time (4)] but both, tunneling and displacement currents, are smaller than what they are previously. This occurs because the potential drop at barrier $(i+2)$ (in the high field domain) is larger than at barrier $(i+1)$. Then there is a smaller overlap between the resonant levels of nearby wells – the tunneling current decreases – and the displacement current and, eventually, $J(t)$ decreases. This stage lasts until well i is drained, and most of the charge is concentrated at wells $(i+1)$ (the local maximum of charge) and $(i+2)$ (slightly smaller charge). Then the next current spike starts.

In summary, we have thoroughly performed an analysis of the time-dependent features of a biased SL. Experimentally observed high-frequency oscillations superimposed on natural oscillations are naturally obtained. For the first time, novel charge density wave dynamics (dipole-like current oscillations) is observed when contact doping is lowered sufficiently. The crossover between monopole and dipole solutions is a function of the sample parameters. Further study of such dependence is the aim of a future work.

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